Demonstration and Comparison of Sequential Approaches to Data Assimilation in HYCOM

A. Srinivasan[1], E. Chassignet, O.M. Smedstad, W. C. Thacker, L. Bertino, P. Brasseur,
T.M. Chin, F. Counillon, and J. Cummings
[1]Center for Ocean-Atmospheric Prediction Studies, Florida State University
phone: (850) 644-7462   fax: (850) 644-4841   email: ashwanth@coaps.fsu.edu

LONG-TERM GOALS

A broad partnership of institutions is collaborating in developing and demonstrating the performance and application of eddy-resolving, real-time global and basin-scale ocean prediction systems using the HYbrid Coordinate Ocean Model (HYCOM). These systems are to be transitioned for operational use by the U.S. Navy at both the Naval Oceanographic Office (NAVOCEANO), Stennis Space Center, MS, and the Fleet Numerical Meteorology and Oceanography Center (FNMOC), Monterey, CA, and by NOAA at the National Centers for Environmental Prediction (NCEP), Washington, D.C. The systems will run efficiently on a variety of massively parallel computers and will include sophisticated, but relatively inexpensive, data assimilation techniques for assimilation of satellite altimeter sea surface height (SSH) and sea surface temperature (SST) as well as in-situ temperature, salinity, and float displacement.

The partnership represents a truly broad spectrum of the oceanographic community, bringing together academia, federal agencies, and industry/commercial entities, spanning modeling, data assimilation, data management and serving, observational capabilities, and application of HYCOM prediction system outputs. The institutions participating in this Partnership have long histories of supporting and carrying out a wide range of oceanographic and ocean prediction-related research and data management. All institutions are committed to validating an operational hybrid-coordinate ocean model that combines the strengths of the vertical coordinates used in the present generation of ocean models by placing them where they perform best. This collaborative partnership provides an opportunity to leverage and accelerate the efforts of existing and planned projects, in order to produce a higher quality product that will collectively better serve a wider range of users than would the individual projects. In addition to operational eddy-resolving global and basin-scale ocean prediction systems for the U.S. Navy and NOAA, respectively, this project offers an outstanding opportunity for NOAA-Navy collaboration and cooperation ranging from research to the operational level.

This effort is part of a 5-year (FY04-08) multi-institutional National Ocean Partnership Program (NOPP) project which includes the Florida State University (E. Chassignet, A. Srinivasan), U. of Miami (G. Halliwell, M. Iskandarani, T. Chin, A. Mariano, Z. Garraffo), NRL/STENNIS (H. Hurlburt, A. Wallcraft, J. Metzger, B. Kara, J. Cummings, G. Jacobs, H. Ngodock, C.A. Blain, P. Hogan, J. Kindle), NAVOCEANO (F. Bub), FNMOC (M. Clancy), NRL/MONTEREY (R. Hodur, J. Pullen, P. May), NOAA/NCEP/MMAB (D.B. Rao, C. Lozano), NOAA/NOS (F. Aikman), NOAA/AOML (C. Thacker), NOAA/PMEL (S. Hankin), Planning System Inc. (O.M. Smedstad), NASA-GISS (R.

Report Documentation Page

1. REPORT DATE **30 SEP 2007**	2. REPORT TYPE **Annual**	3. DATES COVERED **00-00-2007 to 00-00-2007**
4. TITLE AND SUBTITLE **Demonstration And Comparison Of Sequential Approaches To Data Assimilation In HYCOM**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Florida State University,Center for Ocean-Atmospheric Prediction Studies, Tallahassee,FL,32306**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
code 1 only

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**9**	

Bleck), SHOM (R. Baraille), LEGI (P. Brasseur), OPeNDAP (P. Cornillon), U. of S. Mississippi (W. Schmitz), U. of N. Carolina (C. Werner), Rutgers (J. Wilkin, D. Haidvogel), U. of S. Florida (R. Weisberg), Fugro-GEOS/Ocean Numerics (D. Szabo, R. Stephens), Horizon Marine Inc. (J. Feeney, S. Anderson), ROFFS (M. Roffer), Orbimage (L. Stathoplos), Shell Oil Company (M. Vogel), ExxonMobil (O. Esenkov).

OBJECTIVES

The partnership is addressing the Global Ocean Data Assimilation Experiment (GODAE) objectives of three-dimensional (3D) depiction of the ocean state at fine resolution in real-time and provision of boundary conditions for coastal and regional models. It will also provide the ocean component and oceanic boundary conditions for a global coupled ocean-atmosphere prediction model. It will make these results available to the GODAE modeling community and general users on a 24/7 operational basis via a comprehensive data management strategy.

APPROACH AND WORK PLAN

HYCOM development is the result of collaborative efforts among the University of Miami, the Naval Research Laboratory (NRL), and the Los Alamos National Laboratory (LANL), as part of the multi-institutional HYCOM Consortium for Data-Assimilative Ocean Modeling. This effort was funded by the National Ocean Partnership Program (NOPP) in 1999 to develop and evaluate a data-assimilative hybrid isopycnal-sigma-pressure (generalized) coordinate ocean model (Bleck, 2002; Chassignet et al., 2003; Halliwell, 2004). HYCOM has been configured globally and on basin scales at 1/12º (~7 km mid-latitude) resolution, and regionally at 1/25º (~3.5 km mid-latitude) resolution. More details can be found at http://www.hycom.org and in the ONR report by H. Hurlburt.

While HYCOM is a sophisticated model, including a large suite of physical processes and incorporating numerical techniques that are optimal for dynamically different regions of the ocean, data assimilation is still essential for ocean prediction a) because many ocean phenomena are due to flow instabilities and thus are not a deterministic response to atmospheric forcing, b) because of errors in the atmospheric forcing, and c) because of ocean model imperfections, including limitations in resolution. One large body of data is obtained remotely from instruments aboard satellites. They provide substantial information about the ocean's space-time variability at the surface, but they are insufficient by themselves for specifying the subsurface variability. Another significant body of data is in the form of vertical profiles from XBTs, CTDs, and profiling floats *(e.g.,* ARGO). Even together, these data sets are insufficient to determine the state of the ocean completely, so it is necessary to exploit prior knowledge in the form of statistics determined from past observations as well as our understanding of ocean dynamics. We combine all sources of information synergistically to produce the best possible depiction of the evolving ocean. Several techniques for assimilating data into HYCOM are either in place or under development. These techniques vary in sophistication and computational requirements and include: Optimum Interpolation (OI/Cooper-Haines) (PSI, O.M. Smedstad; SHOM, R. Baraille), MVOI/3D-VAR (NRL, J. Cummings; NOAA/NCEP, C. Lozano), SEEK filter (LEGI, P. Brasseur), Reduced Order Information Filter (ROIF) (U. of Miami, T. Chin, A. Srinivasan), Ensemble Kalman Filter (EnKF) (NRL, H. Ngodock; NERSC, L. Bertino), Reduced Order Adaptive Filter (ROAF) (including adjoint) (SHOM, R. Baraille), and the 4D-VAR Representer Method (NRL, H. Ngodock, G. Jacobs). All of these techniques are available for this project and all developers are part of this partnership. A novel experiment to demonstrates and inter-compare the

different approaches listed above is underway. In this report the progress and some preliminary results from this experiment are presented.

RESULTS

Twin experiments are a useful means to gauge the performance of various assimilation schemes since the true state is available. Therefore, a set of identical twin experiments were performed with a 1/12 degree HYCOM configured for the Gulf of Mexico (GOM) domain. In these experiments four different assimilation schemes, a simple Optimal Interpolation (OI), Multivariate Optimal Interpolation (MVOI, Daley 1991; Cummings 2005), Ensemble Optimal Interpolation (ENOI, Evensen 2003) and Ensemble Reduced Order Information Filter (ENROIF, Chin et al., 1999) were used to assimilate synthetic observational data sampled from a truth run. The details of these experiments are listed in Table 1. The GOM domain used here is a sub-region nested inside the standard 1/12° Atlantic domain and is forced by NOGAPS winds. A non-assimilative simulation run from 1999-2003 is used as the truth. This run was used to provide an ensemble of model states needed for statistical analysis by the assimilation schemes and to sample synthetic data under the satellite tracks and MCSST observation locations (Figure 1a). The synthetic data are noise free. In the assimilation experiments, data from the truth run is assimilated into a model initialized from a different initial state as shown in Figure 1b. Although all assimilation schemes use the same observational data in a common format, there are differences in observational information passed to the assimilation engines since some schemes preprocess the data which includes quality control and data thinning operations (see Table 1). All the schemes assimilated observations daily for 50 days starting from August 28, 1999 to October 18, 1999. The data were assimilated once daily and the analyzed state was then used to restart the model. The communication between the assimilation routines and the model is implemented via restart files.

Table 1: Details of the twin experiments including observational processing and vertical projection
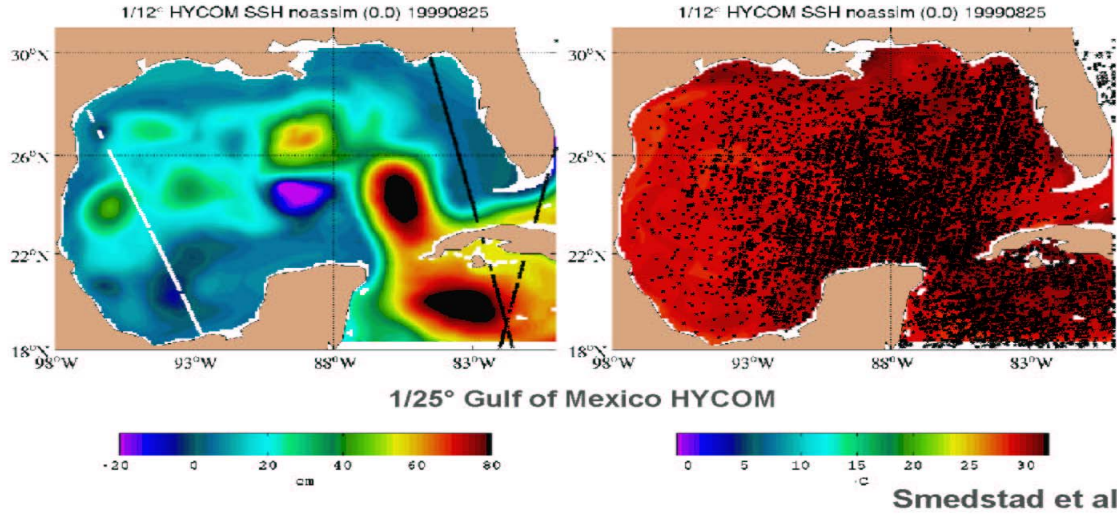
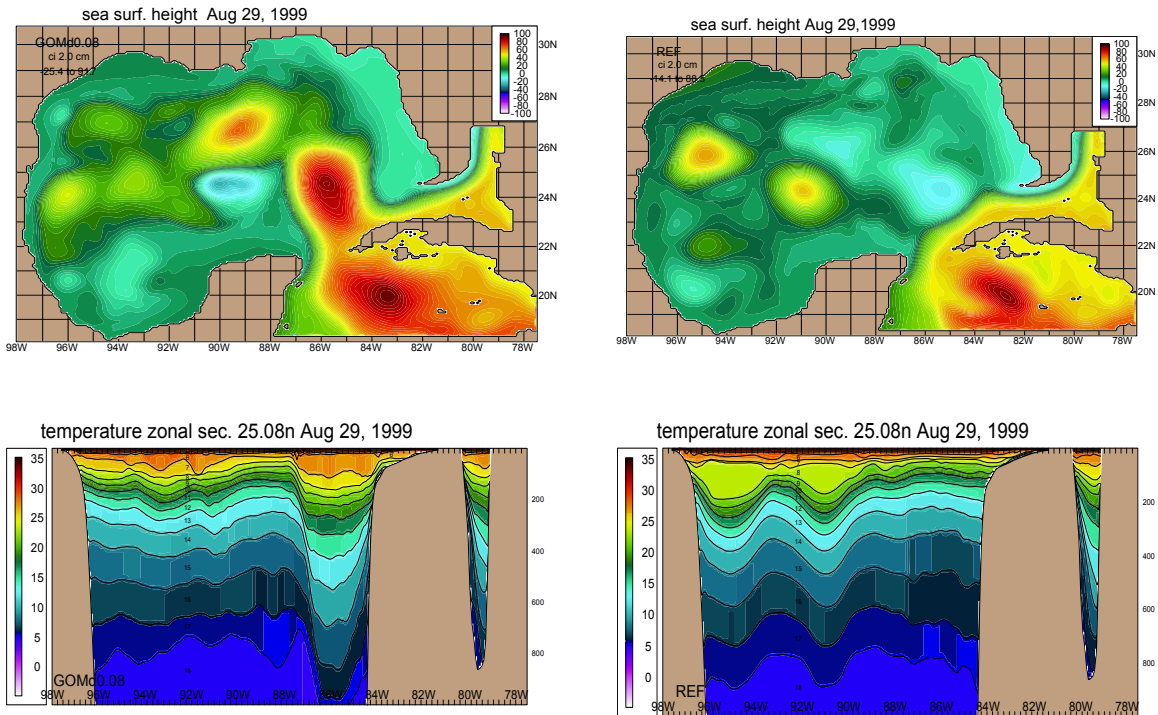| Experiment	Assimilation Scheme	Observations Assimilated	Vertical Projection
Experiment-1	OI/CH	Pre-processed SSH& SST	Cooper-Haines method
Experiment-2	MVOI	Pre-processed SSH&SST	Modified Cooper-Haines
Experiment-3	ENOI	Daily SSH data	Statistical correlations
Experiment-4	ENROIF	Daily SSH &SST data	Statistical correlations

Figure 1: a) Synthetic data sampling locations under altimeter tracks (left panel) and MCSST (right panel) observation locations for a sample day b) SSH and a temperature section showing the initial state of the truth (left panel) and the assimilative runs (right panel)

The sea surface height forecast for day 50 is shown in Figure 2a. It is clearly seen that all the assimilation schemes have moved the model trajectory close to the truth run as compared to the reference run. The SSH RMS error time series shows a reduction in error with time for all schemes The OI and MVOI schemes are both qualitatively and quantitatively closer to the truth than the ensemble methods. The RMS misfits decrease is slowest in the case of ENOI. In this scheme the strength of the assimilation is controlled by an externally specified parameter that ranges form 0 to 1. This parameter was set to 0.5 in the above experiments which reduces the impact of assimilation. It is likely that a steeper decrease in RMS can be achieved by increasing the strength of the assimilation. The spatial distribution of RMS misfits (not shown) indicates that the overall performance of the ENROIF scheme is affected by shallow water areas in the northern Gulf. The current version of ENROIF updates the state using data in shallow water regions which is ideally should not done since altimeter data is of questionable use for shallow water regions.

A key issue in assimilation of surface observations is the projection of the surface signal downward. The OI and MVOI schemes use a dynamical method following Cooper and Haines (1996). The ensemble based schemes use statistical correlations inherent in the 3D covariance matrices to project the surface information downward. The performance of these two methods can be seen in Figure 3a which shows a zonal vertical section across 25.08° N. In general, both approaches are able to capture the vertical structure fairly well. The vertical distribution of domain averaged RMS misfits is shown in Figure 3b. All the schemes are able to reduce the errors in temperature and salinity throughout the water column with the MVOI scheme performing better than the other schemes. However, it should be pointed out that both OI and MVOI schemes are more mature systems at this point and have been tested elaborately with HYCOM. In contrast, these results are the first experiments with the ensemble schemes. These are several parameters that have to be explored and improvements in the performance of these schemes might be forthcoming.

Future work will focus on adding the SEEK scheme to the comparison and further tuning the ensemble based schemes. The data preprocessing and post-processing stage will also be unified. After this a hindcast for the years 2004-2007 is planned as part of this comparison exercise. The consistency and performance of the assimilation schemes will be evaluated by comparing the assimilation runs with the control runs and our general knowledge of the oceanography of the Gulf of Mexico using the following criteria:

1. Skill of the forecasts as compared to the free run of the model.
2. Skill of the nowcasts as compared to the free run of the model
3. Performance measures of the assimilation system based on time series of the innovations and the residuals.
4. Skill of the assimilative lateral boundary conditions for downscaling to nested models in the NOPP CODAE experiment. .
5. Water masses at all depths.
6. Deep circulation.
7. Barotropic stream functions.
8. Mass and velocity structure in the Yucatan and Florida Straits.
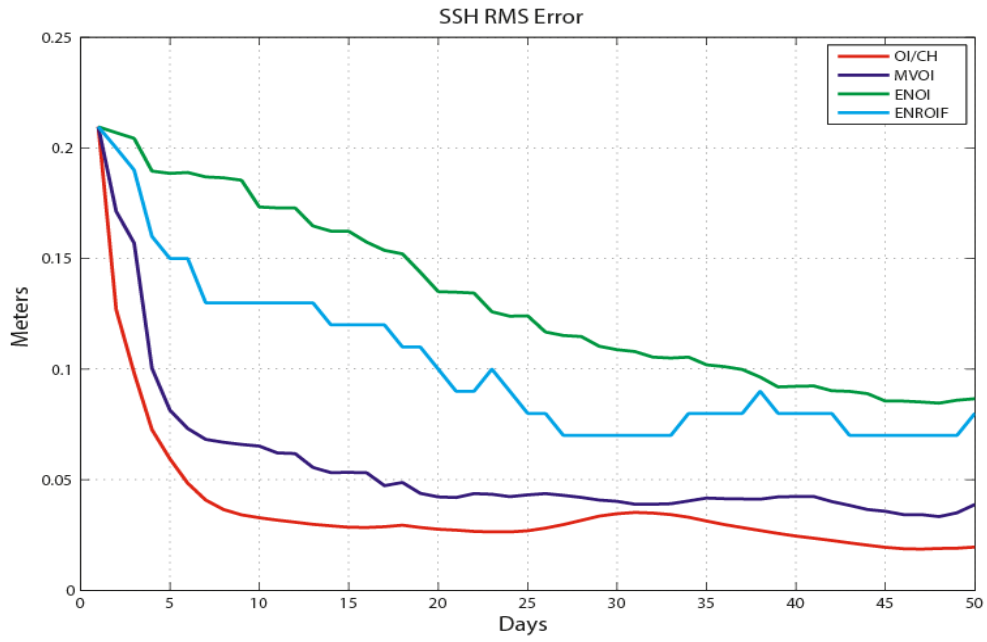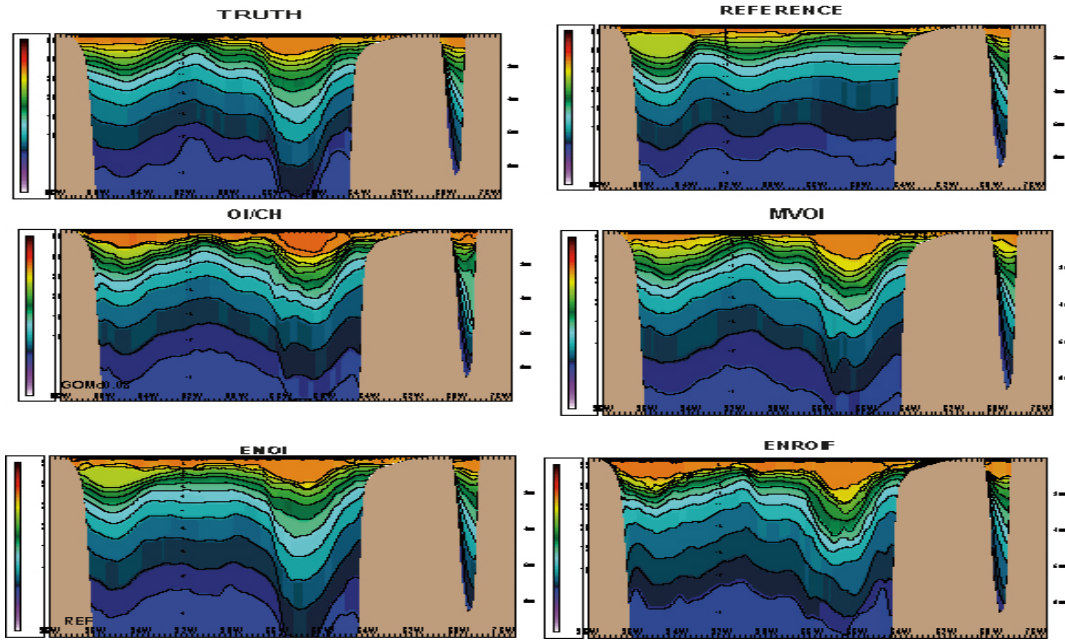
2a)
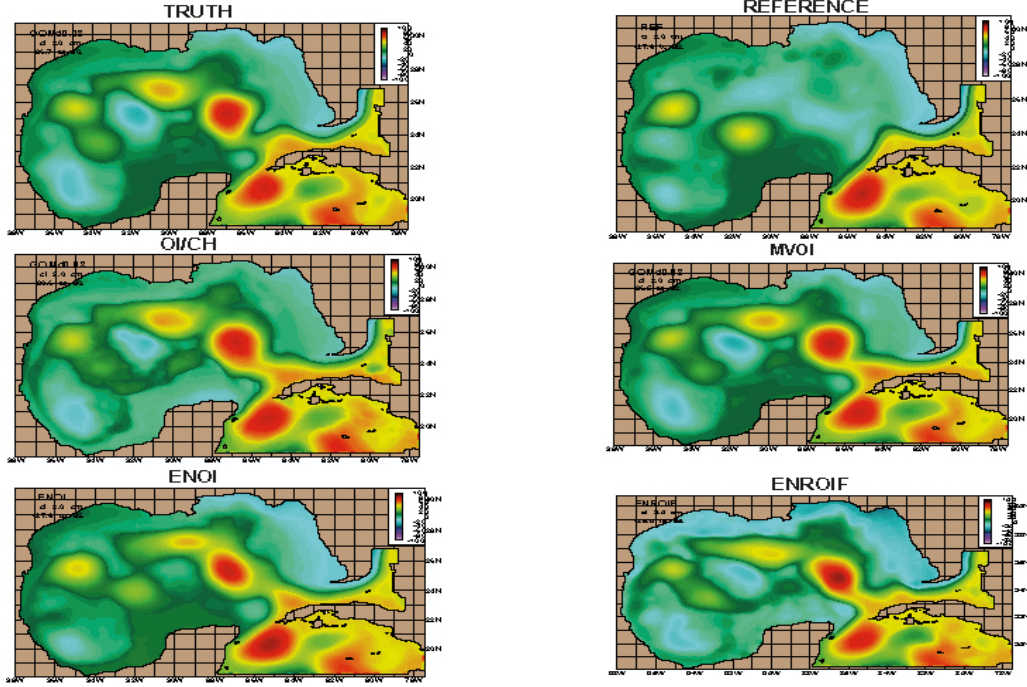
2b)

Figure 2: a) SSH forecast on day 50 compared to the truth and reference runs. b) RMS error time series for the duration of the twin experiments. The figure clearly shows that the assimilation schemes have moved the model trajectory close to the true state.

3a)

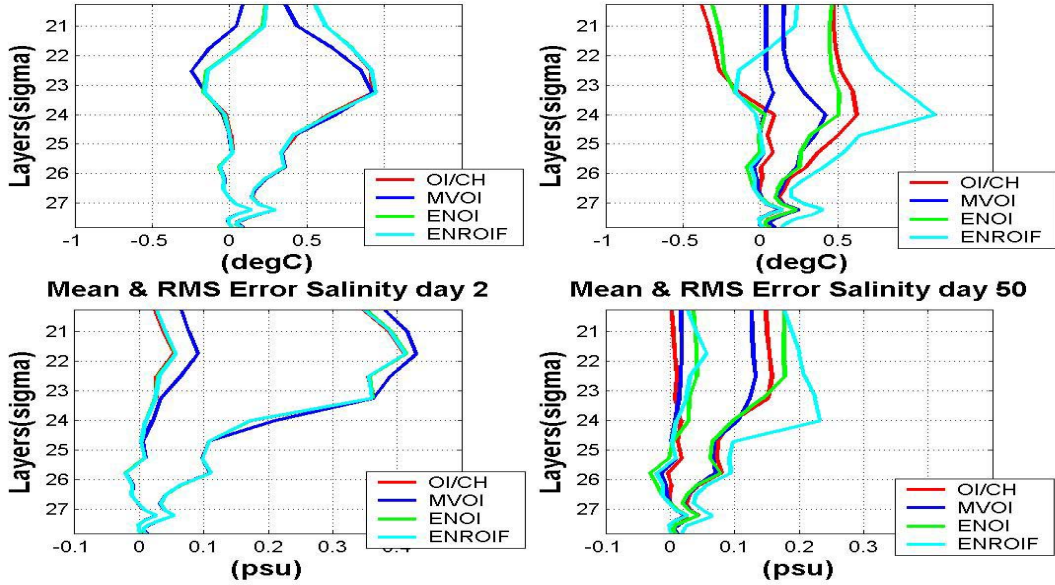Temperature zonal sec. 25.08n Oct 18,1999 (Day 50)

3b)

Figure 3: a) A zonal temperature section showing the effect of vertical projection of surface information. b) The vertical distribution of domain averaged RMS errors in temperature and salinity clear show a reduction in misfits

IMPACT/APPLICATIONS

Three-dimensional (3D) depiction of the ocean state at fine resolution in real-time and provision of boundary conditions for coastal and regional models in the context of the Global Ocean Data Assimilation Experiment (GODAE).

TRANSITIONS

None.

RELATED PROJECTS

This is a highly collaborative NOPP project with 24 partnering groups as listed above. Additionally, the project is receiving grants of super computer time from the DoD High Performance Computing Modernization Office and collaborates closely with the NOPP project led by G. Halliwell entitled "HYCOM Coastal Ocean Hindcasts and Prediction: Impact of Nesting in HYCOM GODAE Assimilative Hindcasts".

REFERENCES

Bleck, R., 2002: An oceanic general circulation model framed in hybrid isopycnic-cartesian coordinates. *Ocean Modelling*, 4, 55-88.

Chin, T.M., A.J. Mariano and E.P. Chassignet, 1999: Spatial regression and multiscale approximations for sequential data assimilation in ocean models. *J. Geophys. Res.*, **104**, 7991-8014.

Cooper, M. and K. Haines, 1996: Altimetric assimilation with water property conservation. *J. Geophys. Res.*, **101**, 1059-1077.

Cummings, J.A., 2005. Operational multivariate ocean data assimilation. *Quart. J. Royal Met. Soc.*, 131:3583-3604.

Daley, R., 1991: Atmospheric Data Analysis. Cambridge University Press, Cambridge, 457 pp.

Evensen, G. 2003: The Ensemble Kalman Filter: theoretical formulation and practical implementation, *Ocean Dynamics*, **53**, 343-367.

Pham, D.T., J. Verron and M.C. Roubaud, 1998: A singular extended filter for data assimilation in oceanography. *J. Marine Sys.*, **16**, 323-340.